ASYMMETRIC HONEYCOMB WALL-FLOW FILTER HAVING IMPROVED STRUCTURAL STRENGTH

Background of Invention

[0001] Honeycomb wall-flow filters are used to remove carbonaceous soot from exhaust of diesel engines. Figure 1A shows a conventional honeycomb wall-flow filter **100** having an inlet end **102**, an outlet end **104**, and an array of interconnecting porous walls **106** extending longitudinally from the inlet end **102** to the outlet end **104**. The interconnecting porous walls **106** define a grid of inlet channels **108** and outlet channels **110**. At the inlet end **102**, the outlet channels **110** are end-plugged with filler material **112** while inlet channels **108** are not end-plugged. Although not visible from the figure, at the outlet end **104**, the inlet channels **108** are end-plugged with filler material while the outlet channels **110** are not end-plugged. Each inlet channel **108** is bordered on all sides by outlet channels **110** and vice versa. Figure 1B shows a close-up view of the cell structure used in the honeycomb filter. The porous walls **106** defining the inlet and outlet channels (or cells) **108**, **110** are straight, and the inlet and outlet cells **108**, **110** have a square cross-section and equal hydraulic diameter.

[0002] Returning to Figure 1A, diesel exhaust flows into the honeycomb filter **100** through the unplugged ends of the inlet channels **108** and exits the honeycomb filter through the unplugged ends of the outlet channels **110**. Inside the honeycomb filter **100**, the diesel exhaust is forced from the inlet channels **108** into the outlet channels **110** through the porous walls **106**. As diesel exhaust flows through the honeycomb filter **100**, soot and ash particles accumulate on the porous walls **106**, decreasing the effective flow area of the inlet channels **108**. The decreased effective flow area creates a pressure drop across the honeycomb filter, which leads to a gradual rise in back pressure against the diesel engine. When the pressure drop becomes unacceptable, thermal regeneration is used to remove the soot particles trapped in the honeycomb filter. The ash particles, which include metal oxide impurities, additives from lubrication oils, sulfates and the like, are not combustible and cannot be removed by thermal regeneration. During thermal regeneration, excessive temperature spikes can occur, which can thermally shock, crack, or even melt, the honeycomb filter.

[0003] It is desirable that the honeycomb filter has sufficient structural strength to withstand thermal regeneration. To avoid the need for frequent thermal regeneration, it is

also desirable that the honeycomb filter has a high capacity for storing soot and ash particles. For a cell structure in which the inlet and outlet channels have equal hydraulic diameter, the effective flow area of the inlet channels can easily become much smaller than that of the outlet channels, creating a large pressure drop across the honeycomb filter. One solution that has been proposed to reducing this pressure drop involves making the hydraulic diameter (or effective cross-sectional flow area) of the inlet channels larger than that of the outlet channels. In this way, as soot and ash particles accumulate on the inlet portion of the porous walls, the effective flow area of the inlet channels will tend to equalize with that of the outlet channels.

[0004] For the conventional honeycomb cell structure shown in Figure 1B, the hydraulic diameter of the inlet cells **108** can be made larger than the outlet cells **110** by reducing the hydraulic diameter of the outlet cells **110**. Figure 1C shows the honeycomb cell structure of Figure 1B after reducing the hydraulic diameter of the outlet cell **110** such that the outlet cell **110** now has a smaller hydraulic diameter in comparison to the inlet cell **108**. Another modification that can be made is to increase the hydraulic diameter of the inlet cells **108**. This modification has the advantage of increasing the effective surface area available for collecting soot and ash particles in the inlet portion of the honeycomb filter, which ultimately increases the overall storage capacity of the honeycomb filter. Figure 1D shows the honeycomb cell structure of Figure 1C after increasing the hydraulic diameter of the inlet cell **108**. Without changing the cell density of the honeycomb filter, any increase in the hydraulic diameter of the inlet cell **108** would produce a corresponding decrease in the thickness of the wall between the adjacent corners of inlet cells **108** (compare t_2 in Figure 1D with t_1 in Figure 1C). As the wall between the corners of the inlet cells become thinner, the structural strength of the honeycomb filter decreases, making the honeycomb filter more susceptible to thermal shock and cracking during thermal regeneration.

[0005] From the foregoing, there is desired a method of improving the storage capacity of the honeycomb filter while maintaining good flow rates through the honeycomb filter without significantly reducing the structural strength of the honeycomb filter.

Summary of Invention

[0006] In one aspect, the invention relates to a honeycomb filter which comprises an array of interconnecting porous walls that define an array of first channels and second

channels. The first channels are bordered on their sides by the second channels and have a larger hydraulic diameter than the second channels. The first channels have a square cross-section, with corners of the first channels having a shape such that the thickness of the porous walls adjoining corners of the first channels is comparable to the thickness of the porous walls adjoining edges of the first and the second channels.

[0007] In another aspect, the invention relates to a honeycomb filter which comprises an array of interconnecting porous walls that define an array of first channels having a square cross-section and second channels having a square cross-section. The first channels are bordered on their edges by the second channels. The edges of the first channels are aligned with edges of the bordering second channels. The first channels have a larger hydraulic diameter than the second channels.

[0008] In yet another aspect, the invention relates to an extrusion die assembly for making a honeycomb filter which comprises a cell forming die having a central region and a peripheral region. The central region comprises an array of discharge slots cut to define an array of first and second pins and an array of first feedholes in communication with the array of discharge slots. The peripheral region comprises at least a second feedhole. The first pins have a larger cross-sectional area than the second pins. The cross-sectional shape of the first pins is selected such that the width of the discharge slots is substantially uniform. The extrusion die assembly also includes a skin forming mask mounted coaxially with the cell forming die and radially spaced from the cell forming die so as to define a skin slot that is in selective communication with the at least second feedhole.

[0009] Other features and advantages of the invention will be apparent from the following description and the appended claims.

Brief Description of Drawings

[0010] Figure 1A is a perspective view of a prior-art honeycomb wall-flow filter.

[0011] Figure 1B shows a standard honeycomb cell structure having inlet and outlet cells with equal hydraulic diameter.

[0012] Figure 1C shows the honeycomb cell structure of Figure 1B after reducing the hydraulic diameter of the outlet cells.

[0013] Figure 1D shows the honeycomb cell structure of Figure 1C after increasing the hydraulic diameter of the inlet cells.

[0014] Figure 2A is a perspective view of a honeycomb wall-flow filter according to an embodiment of the invention.

[0015] Figure 2B shows a honeycomb cell structure having inlet cells and outlet cells with unequal hydraulic diameters and the inlet cells with filleted corners according to one embodiment of the invention.

[0016] Figure 2C shows a honeycomb cell structure having inlet cells and outlet cells with unequal hydraulic diameters and the inlet cells with beveled corners according to another embodiment of the invention.

[0017] Figure 2D shows a honeycomb cell structure having inlet and outlet cells with unequal hydraulic diameters and aligned edges according to another embodiment of the invention.

[0018] Figure 2E is a graph of hydraulic diameter of a cell as a function of fillet radius and cell width.

[0019] Figure 3 is a cross-section of an extrusion die assembly according to one embodiment of the invention.

Detailed Description of Preferred Embodiments

[0020] The invention will now be described in detail with reference to a few preferred embodiments, as illustrated in the accompanying drawings. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the invention. It will be apparent, however, to one skilled in the art that the invention may be practiced without some or all of these specific details. In other instances, well-known features and/or process steps have not been described in detail in order to not unnecessarily obscure the invention. The features and advantages of the invention may be better understood with reference to the drawings and discussions that follow.

[0021] For illustration purposes, Figure 2A shows a honeycomb wall-flow filter **200** according to an embodiment of the invention. The honeycomb filter **200** has a columnar body **202** whose cross-sectional shape is defined by a skin (or peripheral wall) **204**. The profile of the skin **204** is typically circular or elliptical, but the invention is not limited to any particular skin profile. The columnar body **202** has an array of interconnecting porous walls **206**, which intersect with the skin **204**. The porous walls **206** define a grid of inlet channels **208** and outlet channels **210** in the columnar body **202**. The inlet and outlet channels **208**,

210 extend longitudinally along the length of the columnar body **202**. Typically, the columnar body **202** is made by extrusion. Typically, the columnar body **202** is made of a ceramic material, such as cordierite or silicon carbide, but could also be made of other extrudable materials, such as glass, glass-ceramics, plastic, and metal.

[0022] The honeycomb filter **200** has an inlet end **212** for receiving flow, e.g., exhaust gas flow, and an outlet end **214** through which filtered flow can exit the honeycomb filter. At the inlet end **212**, end portions of the outlet channels **210** are plugged with filler material **216** while the end portions of the inlet channels **208** are not plugged. Typically, the filler material **216** is made of a ceramic material, such as cordierite or silicon carbide. Although not visible from the figure, at the outlet end **214**, end portions of inlet channels **208** are plugged with filler material while the end portions of the outlet channels **210** are not plugged. Partial cells near the periphery of the skin **204** are typically plugged with filler material. Inside the honeycomb filter **200**, the interconnected porous walls **206** allow flow from the inlet channels **208** into the outlet channels **210**. The porosity of the porous walls **206** can be variable. In general, the porosity should be such that the structural integrity of the honeycomb filter is not compromised. For diesel filtration, the porous walls **206** may incorporate pores having mean diameters in the range of 1 to 60 μm, more preferably in a range from 10 to 50 μm.

[0023] Figure 2B shows a close-up view of the cell structure of the honeycomb filter **200**. Each inlet cell **208** is bordered by outlet cells **210** and vice versa. To maintain good flow rates when the honeycomb filter **200** is in use, the inlet cells **208** are made to have a larger hydraulic diameter than the outlet cells **210**. In the illustration, the outlet cells **210** have a square geometry. In the illustration, the inlet cells **208** also have a square geometry, but the corners of the square include fillets **218**. One purpose of the fillets **218** is to make the thickness (t_3) between the adjacent corners of the inlet cells **208** comparable to the thickness (t_4) between the inlet cells **208** and the outlet cells **210**. In one embodiment, the thickness t_3 is in a range of about 0.8 to 1.2 times the thickness t_4. Preferably, the radius of the fillets **218** is selected such that the thickness of the porous walls is substantially uniform around the cells. The radius of the fillets **218** may also be selected such that hydraulic diameter of the inlet cells **208** is maximized for a selected cell density and closed frontal area.

[0024] Table 1 below shows examples of cell structures having a cell density of 200 cells/in^2 (about 31 cells/cm^2) and a closed frontal area of 47%. Cell structures A and B are

specific examples of the inventive cell structure shown in Figure 2B. Cell structures C and D are specific examples of the prior-art cell structure shown in Figure 1C.

Table 1

Cell Structure	**Inlet cell hydraulic diameter (mm)**	**Ratio of inlet cell hydraulic diameter to outlet cell hydraulic diameter**	**Inlet cell width (mm)**	**Outlet cell width (mm)**	**Fillet radius (mm)**	**Thickness between adjacent corners of inlet cells (mm)**
A	1.68	1.7	1.59	0.98	0.30	0.54
B	1.73	2.0	1.64	0.88	0.30	0.47
C	1.59	1.7	1.59	0.93	None	0.28
D	1.64	2.0	1.64	0.83	None	0.22

Hydraulic diameter, D_H, of a cell is defined as follows:

$$D_H = \frac{4A}{P} \quad (1)$$

where A is the cross-sectional area of the cell and P is the wetted perimeter of the cell. For a square cell, the hydraulic diameter is the width of the cell. For a square cell with filleted corners, the hydraulic diameter is larger than the width of the cell.

[0025] From Table 1 above, the hydraulic diameters of the inlet cells of the inventive cell structures A and B are larger than the hydraulic diameters of the inlet cells of the prior-art cell structures C and D, respectively. The larger hydraulic diameters of the cell structures A and B are achieved while maintaining the same cell density and closed frontal area as that of the prior-art cell structures C and D. Figure 2E shows how hydraulic diameter varies as a function of fillet radius for a given cell width. The position of the cell structures A, B, C, and D are indicated on the graph. The graph shows that hydraulic diameter has a non-linear relationship with fillet radius. In practice, the inlet cells can be made to have the fillet radius corresponding to the maximum hydraulic diameter achievable for a selected cell width.

[0026] Returning to Figure 2B, the present invention is not limited to inclusion of fillets **218** at the corners of the inlet cells **208**. The corners of the inlet cells **208** could be beveled, for example. Figure 2C shows a cell structure where the corners of the inlet cells

208 include bevels **220**. In this embodiment, the inlet cells **208** have also been enlarged such that the edges of (diagonally) adjacent inlet cells **208** are substantially aligned. This increases the overall storage capacity of the honeycomb filter while allowing good flow rates through the honeycomb filter to be maintained. The bevels **220** (or fillets if used instead of bevels) enable uniformly thick porous walls **206** to be provided around the cells. For the cell structures shown in Figures 2B and 2C, and particularly in Figure 2C, the porous walls **206** are not straight. This leads to an increase in the thermal shock resistance of the honeycomb structure. In the design shown in Figure 2C, portions of the porous walls, e.g., porous wall **206a**, are common to only the inlet cells **208**. These porous wall portions that are common to only the inlet cells **208** could facilitate transfer of heat from one inlet cell to another during thermal regeneration.

[0027] The fillets and bevels can be used to achieve a substantially uniform porous wall thickness throughout the honeycomb filter while maintaining a desired closed frontal area, cell density, and ratio of hydraulic diameter of inlet cell to outlet cell. Typically, a ratio of hydraulic diameter of inlet cell to outlet cell in a range from 1.1 to 2.0, preferably 1.3 to 2.0, more preferably 1.7 to 2.0, is desired. For diesel particulate filtration, a honeycomb having cell density in a range from 10 to 300 cells/in^2 (about 1.5 to 46.5 cells/cm^2), more typically in a range from 100 to 200 cells/in^2 (about 15.5 to 31 cells/cm^2), is considered useful to provide sufficient thin wall surface area in a compact structure. The thickness of the interconnecting porous walls can vary upwards from the minimum dimension of about 0.002 in. (0.05 mm) providing structural integrity, but is generally less than about 0.060 in (1.5 mm) to minimize filter volume. A porous wall thickness in a range of about 0.010 to 0.030 in. (about 0.25 to 0.76 mm), preferably in a range from about 0.010 to 0.025 in. (about 0.25 to 0.64 mm), is most often selected at the preferred cell densities.

[0028] Figure 2D shows another cell structure where the edges of the inlet cells **208** are aligned with edges of the outlet cells **210** and the thickness of the porous walls **206** is uniform throughout the honeycomb filter without the use of a bevel or fillet at the corners of the inlet cells **208**. However, a fillet or bevel to the corners of the inlet cells **208** can further improve the structural strength of the honeycomb filter. The porous walls **206** in this embodiment are even less straight than the porous walls in the embodiments previously described, leading to further improvement in thermal shock resistance.

[0029] Honeycomb extrusion dies suitable for the manufacture of the honeycomb filter described above would have pin arrays including pins of alternating size. The corners of alternating pins could be rounded or beveled. For illustration purposes, Figure 3 shows a vertical cross-section of an extrusion die assembly **300**. The extrusion die assembly **300** includes a cell forming die **302** and a skin forming mask **304**. The cell forming die **300** is used to form the interconnecting porous walls that define the inlet and outlet cells of the honeycomb filter. The cell forming die **302** cooperate with the skin forming mask **304** to define the shape and thickness of the skin of the honeycomb filter. The cell forming die **302** has a central region **306**. An array of discharge slots **308** is cut in the central region **306** to define an array of inlet and outlet pins **310**, **312**. In one embodiment, the transverse cross-section of the inlet and outlet pins **310**, **312** is square, with each corner of the inlet pins **310** including a fillet or bevel.

[0030] The central region **306** of the cell forming die **302** further includes an array of central feedholes **314**, which extend from the inlet face **315** of the die to the array of discharge slots **308**. The central feedholes **314** supply batch material to the discharge slots **308**. The size and location of the central feedholes **314** relative to the discharge slots **308** are selected to achieve a desired flow rate through the discharge slots **308**. As an example, a central feedhole **308** may correspond to each or every other discharge slot **308** or may correspond to each or every other intersection of the discharge slots **308**.

[0031] The cell forming die **302** also includes a peripheral region **316** formed contiguous with the central region **306**. The peripheral region **316** provides a mounting surface **318** for the skin forming mask **304** and includes feedholes **318** for feeding batch material to spaces around the cell forming die **302**. In one embodiment, a shim **320** is interposed between the mounting surface **318** and the skin forming mask **304** to define a skin forming reservoir **322** between the peripheral region **316** and the skin forming mask **304**. The feedholes **318** in the peripheral region **316** supply batch material to the skin forming reservoir **322**. The skin forming mask **304** is radially spaced from the central region **306** to define a skin slot **324**, which is in communication with the skin forming reservoir **322**. Batch material is extruded through the skin slot **324** to form the skin of the honeycomb filter. The volume of the reservoir **322** can be adjusted to control the rate at which batch material is supplied into the skin slot **324**.

[0032] In operation, batch material is fed into the feedholes **314**, **318** in the cell forming die **302** and extruded through the discharge slots **308** and the skin forming slot **324**. The volume of the batch material in the skin forming reservoir **322** is dependent on the extent of the radial overhang of the skin forming mask **304** over the skin forming reservoir **322**. The rate of flow of batch material into the skin forming slot determines the character of the skin, while the rate of flow of batch material into the discharge slots determine the character of the porous walls.

[0033] The extrusion die assembly described above can be manufactured using existing methods for making extrusion dies. The cell forming die may be made by machining holes in a lower portion of a block that is made of a machinable material. These holes would serve as feedholes. A process such as plunge electrical discharge machining can be used to cut the discharge slots in the upper portion of the block. Pins remain on the upper portion of the block after the slots are cut. The pins at the periphery of the block can be shortened or completely removed to provide a mounting surface for the skin forming mask. The discharge slots could have any of the geometries described above in conjunction with the cell structure of the honeycomb filter.

[0034] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.